MODIFIED OPERATING SCENARIOS FOR THE G-2 AND MU2E EXPERIMENTS

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E. Prebys, P. Adamson, G. Annala, B. Casey, M. Convery, P. Derwent, J. Dey, C. Jensen, S. Johnson, I. Kourbanis, V. Nagaslaev, G. Vogel, S. Werkema, R. Zwaska
Fermilab

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Executive Summary

The Fermilab Booster is a rapid cycling synchrotron, which operates at a fixed frequency of 15 Hz. This frequency is the basis of all sequencing within the accelerator complex. Individual cycles are referred to as "ticks", and the protons accelerated on a cycle are referred to as a "batch". The full Main Injector cycle planned for the NOνA Experiment requires 20 ticks, or 1.33 seconds, but uses only 12 Booster batches. Until recently it had been assumed that all of the remaining 8 ticks would be available for the Recycler Ring beam manipulations required for Muon Campus experiments. Under that assumption, the experiments could operate without impacting proton delivery to NOνA; however, a more careful analysis has shown this is not the case. Certain hard and soft timing constraints, in systems throughout the Fermilab accelerator complex, require spacing between the beams to different experiments. Consequently, the actual time available for Muon Campus beam manipulation is less than that initially assumed in planning for g-2 and Mu2e. Moreover, it has been found that imposing these timing constraints on the original Muon Campus operating scenario would have significant adverse impacts on the two experiments. In the case of g-2, it would only allow three of the four planned Booster batches to be loaded, reducing the average proton rate to the experiment by 25%. Mu2e, on the other hand, only uses two Booster batches; however, when the correct model for the timeline is used, the time available for slow extraction is reduced, resulting in a unacceptably high instantaneous rates in the Mu2e detectors.

Impacts to NOνA, g-2, and Mu2e are shown below for the nominal timeline (20 ticks total length, 12 NOνA batches), as well timelines that have been modified to increase the time available for Muon Campus beam manipulation in the Recycler Ring:

g-2			
Total ticks	NOνA Batches	Relative g-2 rate[1]	Relative NOνA rate[1]
20	12	75%	100%
20	11	100%	92%
21	12	95%	95%

[1] The numbers in this column are rates relative to the proton delivery rate expected in the original operating scenario.

Mu2e				
Total ticks	NOνA Batches	Relative Mu2e total rate[1]	Relative NOνA rate[1]	Peak Detector Rate Factor[2]
20	12	100%	100%	1.61
20	11	100%	92%	1.27
20	10	100%	84%	1.04
21	12	95%	95%	1.27
21	11	95%	87%	1.04
22	12	91%	91%	1.04

We see that the 20 tick timeline with 12 NOνA batches significantly reduces the proton delivery rate to g-2 and increases the peak rate to the Mu2e detectors by 67%; a rate that is unacceptably high [1]. If the rate is indeed too high, the total proton rate will have to be reduced to bring it down to acceptable levels. Increasing the timeline to 21 ticks, or removing one batch from NOνA, would restore the g-2 experiment to the nominal number of protons per Main Injector cycle. It would also reduce the increase in peak intensity to Mu2e to an acceptable level. The NOνA beam would be correspondingly reduced.

The exact time line can be quickly changed during down time or commissioning of g-2 or Mu2e to optimize beam delivery to NOνA, and vice versa. It is also possible to change time lines at different times or on different days to fine-tune the trade off between the experiments.

All these decisions regarding the proton delivery time line ultimately rest with Program Planning, and it is hoped the information in this document will help inform those decisions.

[2] The numbers in this column are instantaneous rates in the Mu2e Detectors relative to the rates expected in the original operating scenario.

1. Introduction

This section describes the parts of the Fermilab accelerator complex relevant to g-2 and Mu2e beam delivery. Also included are some relevant details about the accelerator Time Line Generator (TLG), which is responsible for sequencing operations in the various subsystems.

In all cases, beam energy refers to the kinetic energy of the beam.

1.1 The Fermilab Accelerator Complex

The parts of the Fermilab Accelerator Complex that will be used for the g-2 and Mu2e experiment are the Linac, the Booster, the Recycler, the Delivery Ring, and associated beamlines. The experiments don't directly use the Main Injector, but understanding the Main Injector acceleration cycle during the NOνA era is important to this discussion.

The former antiproton production target and antiproton Debuncher ring (now called the Delivery Ring) have been re-tasked as part of what is now referred to as the "Muon Campus".

1.1.1 The Linac

The Linac is the beginning of the accelerator chain and the source of all protons at Fermilab. It consists of several subsystems, the details of which are not germane to this discussion. It produces pulses of 400 MeV H^- ions in 15 Hz pulse trains, based on the acceleration cycle of the Booster.

1.1.2 The Booster

The Booster is a rapid cycling synchrotron that accelerates protons from 400 MeV to 8 GeV. The two electrons are stripped from the Linac's H^- ions during multi-turn injection. The Booster operates in a 15 Hz offset resonant circuit, which sets a fundamental clock for the entire complex. Each 15 Hz cycle is referred to as a "tick", and the protons accelerated on each cycle are referred to as a "batch".

Individual batches can vary in size, and can be individually sent to different locations. The potential destinations for Booster protons are currently:

- A beam dump, which is used for study cycles
- The 8 GeV Booster Neutrino Beam (BNB)
- The Main Injector
- The Recycler (discussed in the next subsection)

Batches can achieve a maximum intensity of about 5×10^{12} protons, although both the g-2 and Mu2e experiments are planning on batches of 4×10^{12} to maintain the best beam quality.

The bunch structure of the Booster beam is determined by the harmonic 84 RF system, which is approximately 53 MHz at extraction. Three bunches are removed early in the cycle to allow for the rise time of the extraction kicker, so the extracted beam consists of a bunch train of 81 bunches, separated by about 19ns – about 1.6 μsec total length.

1.1.3 The Main Injector

The Main Injector is not used by the Muon Campus experiments, but its cycle is an important consideration. For the high-energy neutrino program, the Main Injector is used to accelerate protons from 8 to 120 GeV. The total time it takes to accelerate the protons, extract them, and return the Main Injector to its initial energy for more protons is currently 20 “ticks”, or 1.33 seconds. During MINOS/Tevatron operation, 11 Booster batches were loaded into the Main Injector prior to acceleration, adding an additional 11/15 of a second to the cycle. The time required for the Main Injector acceleration time was also somewhat longer in that era, bringing the total cycle time to a little over 2 seconds.

During the NOνA era, the upgrades discussed in the next section allow protons to be stacked in the Recycler, thereby eliminating the loading time from the Main Injector. In addition, RF stations were added to the Main Injector to reduce the acceleration time to its current value of 1.33 s. The reduced cycle time and other improvements bring the NOνA design beam power to 700 kW.

1.1.4 The Recycler

The Recycler is an 8 GeV permanent magnet storage ring, which shares a tunnel with the Main Injector. The Recycler was originally built in the Tevatron Collider era to store antiprotons that had been recovered from the Tevatron and store and cool them for reuse. It was never used for that purpose, but was instead used to store antiprotons that had been produced in the Antiproton Source. Moving antiprotons from the Antiproton Accumulator to the Recycler allowed for a higher average antiproton stacking rate, and paved the way for the high luminosities at the end of the Tevatron program.

During the Tevatron program, all particles injected into, or extracted from, the Recycler had to pass through the Main Injector. After the Tevatron program ended, modifications were made to allow protons to be directly injected from the Booster into the Recycler. This allows protons to be stacked in the Recycler prior to being loaded into the Main Injector. This reduces the total cycle time, thereby increasing the average power.

Both the Recycler and the Main Injector are seven times the Booster diameter. After allowing for kicker rise and fall times, this leaves six useable “slots” in which to inject beam. To increase the amount of beam for the neutrino program, both machines use a technique known as “slip stacking”. In the case of Recycler slip stacking, the first six batches are loaded and slightly decelerated. Thus, when new Booster batches are injected, they are moving at a slightly different velocity than the decelerated batches causing them to “slip”, relative to the batches that are already there. Six subsequent batches are loaded in this way, for a total of 12. At a certain time (determined by the revolution frequency difference between the two sets of six batches) the first six batches and the last six batches align in azimuth and are extracted to the Main Injector as six double batches. Because the Main Injector cycle takes 20 ticks, this means there are eight ticks, and potentially eight Booster batches, which *cannot* be used by NOνA.

Both g-2 and Mu2e intend to use both the Booster and the Recycler during these eight ticks. For this reason, an additional extraction line is being added to extract beam directly from the Recycler to the Muon Campus. Also, a 2.5 MHz RF system will be installed in the Recycler, to re-bunch each Booster batch into four 2.5 MHz bunches.

1.1.5 Sequencing and the Time Line Generator

Beam transfer, acceleration, and manipulation involve a complex coordination of the various components of the Fermilab accelerator complex. This coordination is accomplished by the Time Line Generator (TLG). Individual actions are triggered by a particular "reset", identified by a two digit hexadecimal number, and distributed by the TLG. For example, a $1D TLG reset tells the accelerator control system that a batch is destined for the Booster Neutrino Beam.

2. Beam Delivery to the Experiments

Both muon experiments use the Recycler in similar ways, and both use the former Antiproton Source, although they each use it in very different ways.

The former Antiproton Accumulator Ring has been removed, while the Antiproton Debuncher is being kept for use in both experiments, and is now referred to as the "Delivery Ring".

2.1 g-2 Beam Delivery

In the case of g-2, one or two Booster batches are injected into the Recycler and re-bunched into four or eight 2.5 MHz bunches. These are extracted one at a time to the former antiproton production target and Lithium lens to produce a secondary muon beam.

Muons from the production target are injected into the Delivery ring. The Delivery Ring is used to store muons for several turns, until all pions have decayed away and the muons can be transferred to the g-2 storage ring. For g-2 operation, the Delivery Ring is set to the "magic momentum" of 3.1 GeV/c. At this momentum the electrostatic quadrupoles in the g-2 storage ring do not contribute to the precession of the circulating muons.

2.2 Mu2e Beam Delivery

Mu2e also uses 2.5 MHz bunches from the Recycler, but the subsequent handling is quite different. The proton bunches bypass the production target and are injected directly into the

Delivery Ring, which, in this case, is set to match the 8 GeV energy of the Recycler. From the Delivery Ring, protons are resonantly extracted over tens of milliseconds to the Mu2e experiment. This process generates short pulses, separated by the 1.7 μsec revolution period of the Delivery Ring.

2.3 Baseline Proton Delivery Timelines

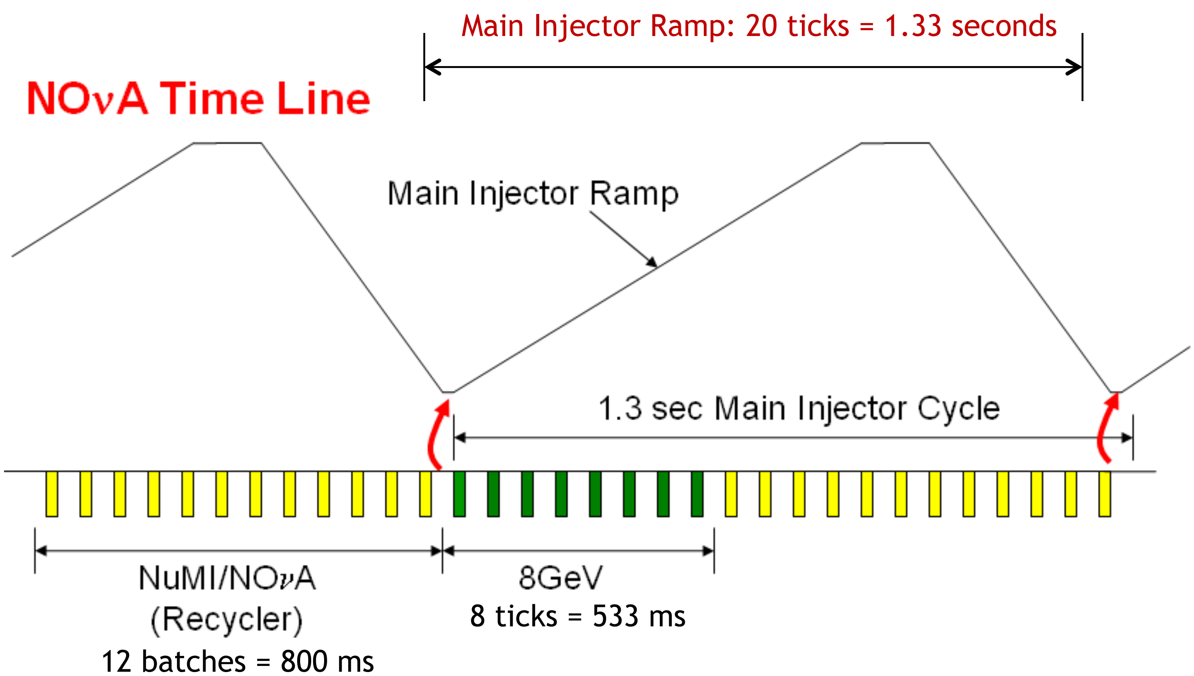

Figure 1: NOνA time line, showing batches available to other experiments.

As stated earlier, the NOνA time line uses 12 out of 20 available Booster batches for the NOνA experiment, leaving 8 batches available for other use, as illustrated in Figure 1. While neither the g-2 nor the Mu2e experiment planned to use all eight bunches, both assumed they would have the entire 8 ticks – or 533 msec – available for beam manipulation in the Recycler.

2.3.1 g-2 Beam Delivery

The baseline g-2 delivery scheme involved injecting a 4×10^{12} proton Booster batch into the Recycler, re-bunching it into four 2.5 MHz bunches of 1×10^{12} protons each, and extracting these one at a time to the muon production target at 10 msec intervals. This minimum Recycler extraction interval is determined by the maximum pulse rate of the Lithium lens.

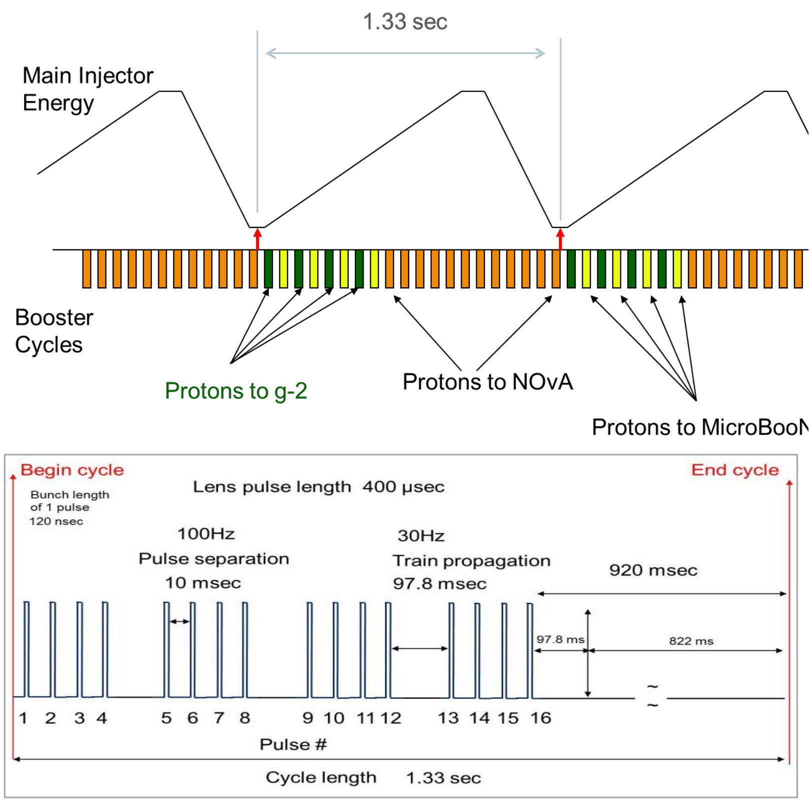

Figure 2: Baseline g-2 time line.

This sequence would be repeated four times each Main Injector cycle, for a total of 16 transfers to the g-2 Experiment each NOνA cycle, as illustrated in Figure 2.

2.3.2 Mu2e Beam Delivery

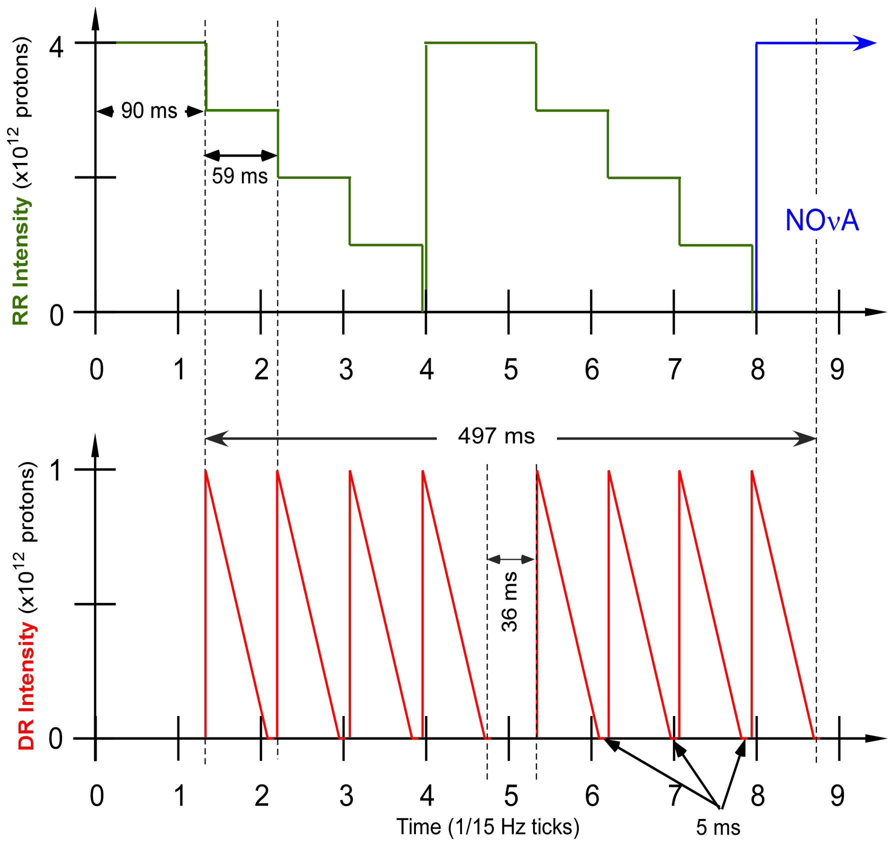

Figure 3: Baseline beam delivery time line for Mu2e

Like g-2, Mu2e beam delivery begins with the transfer of a Booster batch to the Recycler subsequent re-bunching into four 2.5 MHz bunches of 1×10^{12} protons each. In this case, however, these bunches are extracted directly to the Delivery Ring, bypassing the production target. The protons circulating in the Delivery Ring are then slow extracted to the Mu2e experiment. The baseline plan of the experiment is to use two Booster batches per NOνA cycle, for a total of eight Recycler to Delivery Ring transfers. In order to minimize the instantaneous rate in the detector, the experiment planned to stretch out the operation as much as possible in the Recycler. Assuming the entire eight ticks are available, this results in 59 ms per transfer to the Delivery Ring, as shown in Figure 3. After a 5 ms setup time in the Delivery Ring, each bunch is extracted over 54 ms. This assumption has set the baseline instantaneous rate for the design of the Mu2e detectors [2].

3. Constraints to Time Line Usage

It came to our attention that the Muon Campus experiments were making some naïve assumptions regarding the required manipulations, so a task force was assembled to consider all potential problems with beam delivery for these experiments, to arrive at realistic operational schemes. The task force included representatives of all of the accelerators involved, as well as experts in kickers, low and high level RF, the accelerator control system, and the time line generator. These experts are all represented in the authorship of this paper.

3.1 Slip-Stacking "13th Batch" Issue

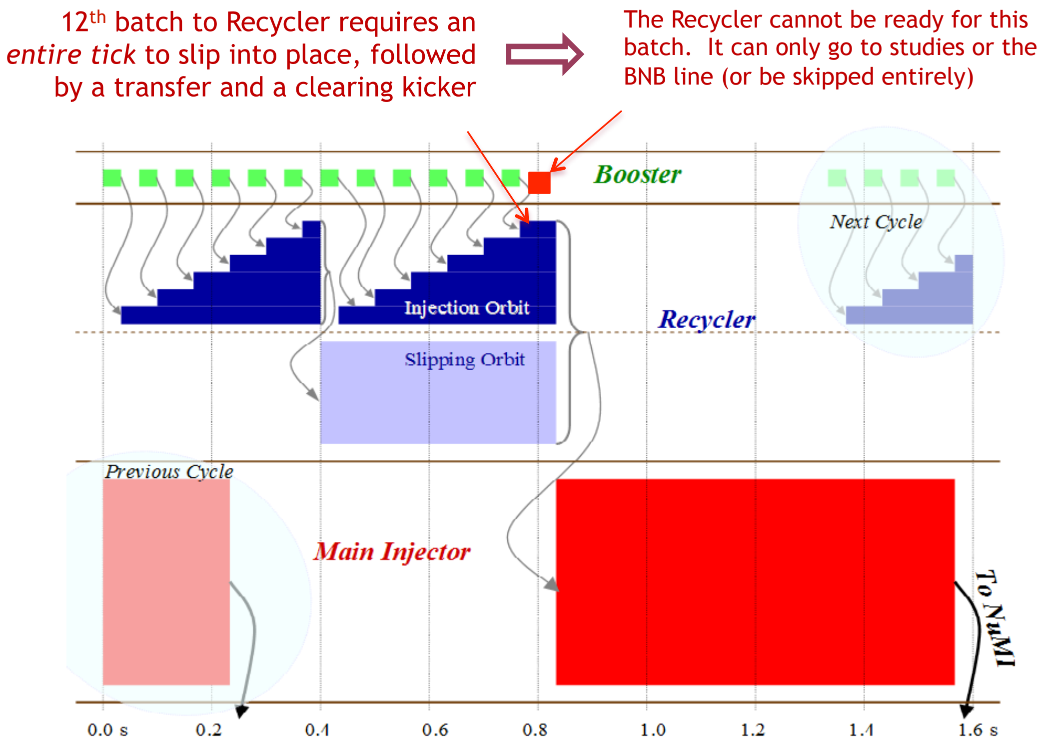

Figure 4: Schematic illustration of slip-stacking for NuMI, indicating the "13th Batch" problem.

The revelation that triggered this study was the realization that the Booster batch immediately after the 12 batches that had been loaded for NOνA would not be available for use by either g-2 or Mu2e. This is because the *entire* 12th tick is required for the two sets of batches to slip together, after which beam must be transferred to the Main Injector and a clearing kicker must be fired and allowed to recharge (because it also serves as the abort kicker for the next batch). Therefore this next batch must be sent to the BNB line, the Booster dump, or be skipped entirely. In a 20 tick time line, this immediately reduces the time available for beam manipulation in the Recycler from eight ticks (533 ms) to seven ticks (467 ms).

3.2 Beam Initiation and Booster Ramp Time Line Issues

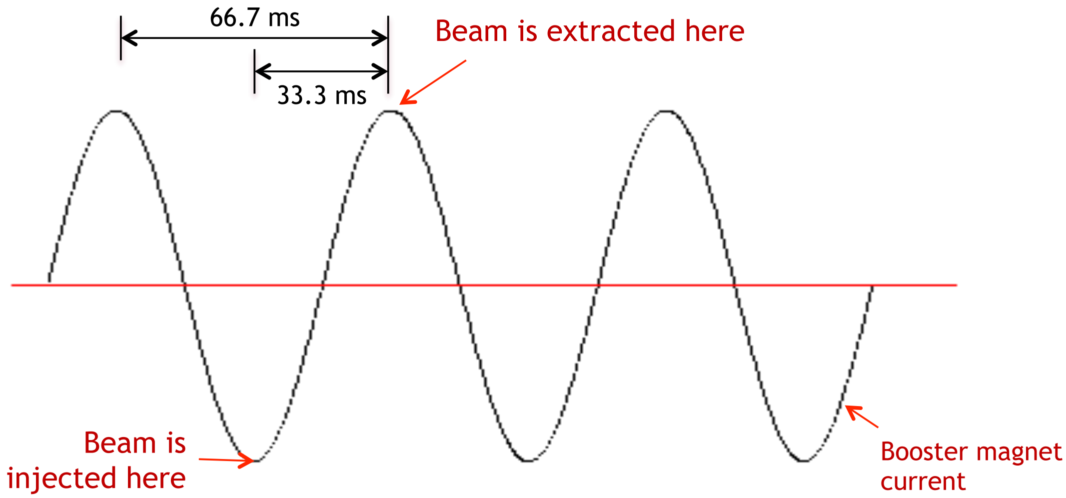

Figure 5: Booster cycle with injection and extraction indicated

As was discussed earlier, the Time Line Generator controls all actions in the accelerator complex. The Booster is rather a special case in that the destination for each Booster cycle must be specified before beam is injected; in fact, it must be specified before beam is initiated in the Linac. Since the Booster runs at 15 Hz, the destination must be known at least 33.3 ms before beam is injected, as illustrated in Figure 5. Once certain end effects are added to the required sequence, this time is increased to 37 ms [3].

Because of the way the Time Line Generator functions, the Recycler must be ready for beam *before* beam intended for the Recycler can be injected into the Booster. Thus, any g-2 or Mu2e beam must be extracted from the Recycler and the clearing kicker fired at least 37 ms before the first NOνA batch is injected. The net effect is to subtract an additional 37 ms from the time available, in addition to the full tick discussed in the previous section.

3.3 Recycler Bunching Time

Both the g-2 and Mu2e experiments require a narrow proton beam pulse[3]. This narrow shape is primarily accomplished by a re-bunching RF sequence in the Recycler that re-bunches the 81 53 MHz bunches in a Booster batch into four 2.5 MHz bunches. The baseline Recycler RF sequence consisted of a 10 ms turn-off of the 53 MHz system followed by a 90 ms ramp up of the 2.5 MHz RF system. In the scenarios considered in this report, the 53 MHz turn-off time was shortened to 5 ms and the 2.5 MHz ramp was shortened to 85 ms. This reduction in the adiabaticity of the two RF ramps will cause a small increase in the width of the resulting 2.5 MHz bunches extracted to the Muon Campus. ESME simulations of the Recycler RF

[3] The g-2 experiment requires that the 95% full width of each proton bunch striking the production target be less than 149 ns. Mu2e requires a full width of less than 250 ns with the additional requirement that the beam between proton pulses (outside of the 250 ns window) be extinguished at the 10^{-10} level. A separate extinction system in the beamline between the Delivery Ring and the Mu2e proton target accomplishes much of the inter-pulse clearing. However, the Mu2e extinction requirement implies that Mu2e is fundamentally concerned about the longitudinal tails of the beam.

systems show that this width increase is very small and does not cause the 2.5 MHz bunches delivered to the Muon Campus to exceed the width requirements of either experiment.

An additional impact to the Mu2e experiment is that the faster RF ramps will be less efficient at moving all of the beam to the core of the bunch during re-bunching. Consequently, the amount of beam outside of the 250 ns beam window will increase with faster ramps. This will decrease the margin to the Mu2e extinction requirement.

3.4 Lithium Lens Pulse Rate (g-2 Only)

Pulses of the Lithium lens for the g-2 muon production must be separated by at least 10 ms, limited by the time necessary to recharge the pulsing circuit. Thus bunches can only be extracted from the Recycler to g-2 with a minimum of 10 ms separation. Moreover, the Lithium lens can be pulsed up to eight times in a row, which will be important for the alternate scenario discussion below.

3.5 Delivery Ring Abort Kicker (Mu2e Only)

During Mu2e operation of the Delivery Ring an abort kicker must be fired at the conclusion of each spill to clear any remaining beam prior to injection of the next bunch. This limits the time between Delivery Ring injections to a minimum of 35 ms. An additional 5 ms is required to set up for the next slow extraction. Thus, the minimum Recycler extraction / Delivery Ring injection interval during Mu2e operation is 40 ms. Even if it were possible to shorten this minimum time[4], achieving a stable slow extraction over a shorter time interval would be problematic.

3.6 Possible Amelioration

The task force extensively discussed whether it would be possible to ameliorate any of the restrictions discussed above.

In particular, it appeared that the required 37 ms gap discussed above could be addressed with a modification to the time line controls system. While this is true in principle, it would require extensive modification of the fundamental way in which the system operates. Because this involves beam protection and personnel safety systems, extensive review would also be required. Even determining the scope of work and required was beyond the mandate of this task force, but it would certainly be at the level of an AIP, if not more.

There further exists the problem of clearing beam from the Recycler and being immediately ready to use the same kicker as abort kicker. This could be solved with a dual pulse power supply, at a cost on the order of several hundred $k, or changes to the operational requirements of a full-turn kicker.

Two ideas have been proposed to eliminate the "13th batch" problem. The first is to increase the frequency separation of the two sets of batches after the 12th one is injected, thereby speeding up

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[4] Given sufficient money, time, and people it is indeed possible to shorten this time.

the slipping time (saving 5-20 ms). The second would be to transfer the batches to the Main Injector before they had entirely slipped together (saving a further few ms). A combination of the two is also possible. However, high-intensity slip-stacking is not yet fully operational in the Recycler, and either of these solutions would require extensive study after it is operational, just to establish the feasibility.

The group agreed that the most responsible way to proceed is to adopt a conservative approach, and treat the limitations described in the previous sessions as immutable, and evaluate the impacts accordingly. Future study groups could evaluate more aggressive attempts to recover time, at a correspondingly greater expenditure of effort.

4. Impact and Alternate Scenarios

In this section, we evaluate the impact of this constraint on both experiments and discuss possible alternate beam delivery scenarios. In all cases, the term "baseline scenario" refers to a 20 tick timeline, with 12 batches going to NOνA each cycle.

4.1 g-2 Experiment

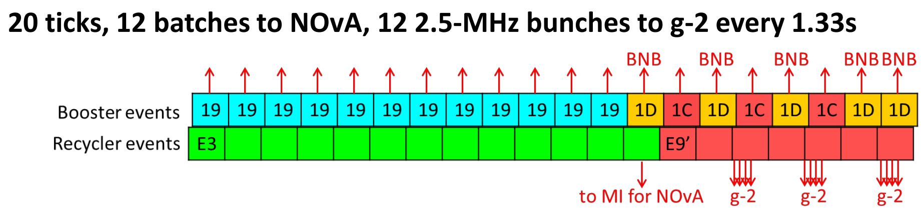

Figure 6: g-2 beam delivery in the baseline time line scenario. The hexadecimal numbers in each box refer to the event Time Line Generator event types in each machine.

In the case of g-2, it is found that in the baseline, there is simply not enough time to extract all 16 bunches from the Recycler. Consequently, the entire fourth Booster batch must be skipped – a 25% reduction in beam to the experiment, as illustrated in Figure 6.

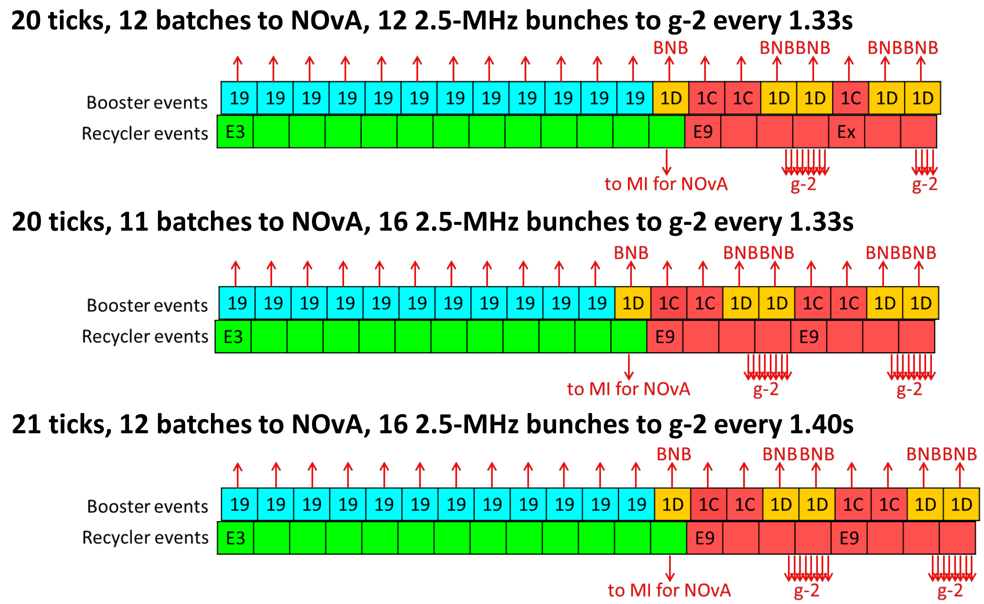

Figure 7: g-2 time lines in which two Booster batches have been injected into the Recycler prior to rebunching.

It was found that the available time could be used more effectively by injecting two consecutive Booster batches and re-bunching them to eight 2.5 MHz bunches, rather than re-bunching a single batch to four. This is still not sufficient to deliver four booster batches to the g-2 in the baseline time line; however, it would be possible if either one batch were removed from NOνA or one tick were added to the time line, as illustrated in Figure 7. The impacts to g-2 and NOνA of these two scenarios are summarized in Table 1

Total ticks	NOνA Batches	Relative g-2 rate	Relative NOνA rate
20	12	75%	100%
20	11	100%	92%
21	12	95%	95%

Table 1: Impacts to g-2 and NOνA of various running scenarios, relative to the baseline.

4.2 Mu2e Experiment

The impact on the Mu2e experiment is not quite as straightforward to calculate as that for the g-2 experiment. Implementation of the baseline scenario as described in the Mu2e TDR (see Figure 3) and imposing the recently discovered timing constraints requires a recycler extraction interval of 23 ms. This interval is shorter than the 40 ms minimum time required to reset the Delivery Ring and recharge the Delivery Ring abort kicker described in section 3.5. Consequently, preservation of the original TDR scenario would require the elimination of the second Mu2e designated Booster batch, resulting in a 50% reduction in the beam delivered to Mu2e.

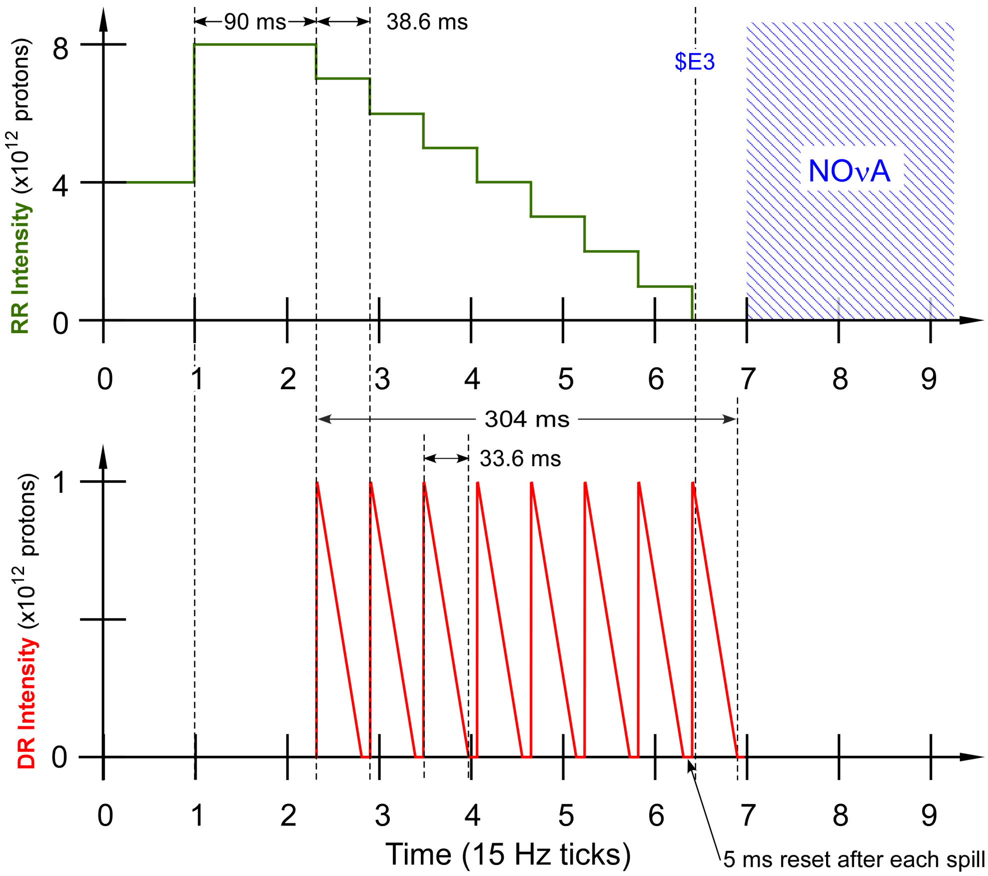

Figure 8: Time Line for Mu2e in the baseline NOνA scenario.

Like g-2, it was found that it was advantageous to start by transferring two Booster batches to the Recycler and re-bunching them into eight bunches, rather than re-bunching one batch into four bunches. The resulting time line is shown in Figure 8 for the baseline NOνA scenario. The Recycler extraction interval in this time line is 39 ms. This interval is slightly below the 40 ms requirement of section 3.5, but could probably be made to work.

A more serious issue is the number of protons per pulse on the Mu2e target in this scenario. Shortening the Recycler extraction interval also shortens the time available for slow spill from the Delivery Ring, thereby increasing the instantaneous rate to the experiment. If the same intensity Booster batches are used, this time line results in a 61% increase in peak intensity relative to the Mu2e TDR baseline. To reduce the instantaneous rates to an acceptable level one could reduce the intensity of the Booster batches, at a cost of reducing the total integrated protons on the Mu2e target. Both alternatives – either a 61% increase in rates or a similar reduction in beam delivered to the experiment – present an unacceptable adverse impact to Mu2e.

Adding a tick to the time line, or removing a batch from NOνA, would reduce the instantaneous rate to a 27% increase relative to the Mu2e baseline. This increase is much more likely to be accommodated by the Mu2e experiment. Recovery of the Mu2e baseline intensity per pulse on target requires the addition of at least two extra ticks to the accelerator timeline. The impacts of the various scenarios on Mu2e and NOνA are summarized in Table 2.

Total ticks	NOvA Batches	Relative Mu2e total rate	Relative NOvA rate	Peak Rate Factor
20	12	100%	100%	1.61
20	11	100%	92%	1.27
20	10	100%	84%	1.04
21	12	95%	95%	1.27
21	11	95%	87%	1.04
22	12	91%	91%	1.04

Table 2: Impact of various running scenarios on Mu2e. In all cases, Booster batch size could be reduced, lowering the peak rate factor and total rate by the same amount.

A final impact to the Mu2e experiment is the addition of beam to the tails of the longitudinal distribution as a consequence of the faster Recycler RF ramps. An ESME simulation of the Recycler RF manipulations for Muon Campus beam shows that shortening these Recycler RF ramps has the effect of approximately doubling the amount of beam outside of the Mu2e 250 ns window [4]. It is believed that this amount of excess beam in the longitudinal tails still leaves considerable margin to the Mu2e extinction requirements.

4.3 Verification

To test the feasibility of these scenarios, the first half of a g-2 cycle was modeled using the spare Time Line Generator. This processor is functionally identical to the operational TLG, and all the same sequencing rules must be obeyed. The resulting time line is shown in Figure 9, which establishes that one can inject two Booster batches, re-bunch them into eight 2.5 MHz bunches and extract them to the g-2 production target within 4 Booster ticks. This sequence is simply repeated twice to give the proposed g-2 time line. In the case of Mu2e, the injection and re-bunching are identical to this time line, and the extractions are simply spaced further apart, so this also establishes the feasibility of the Mu2e time line.

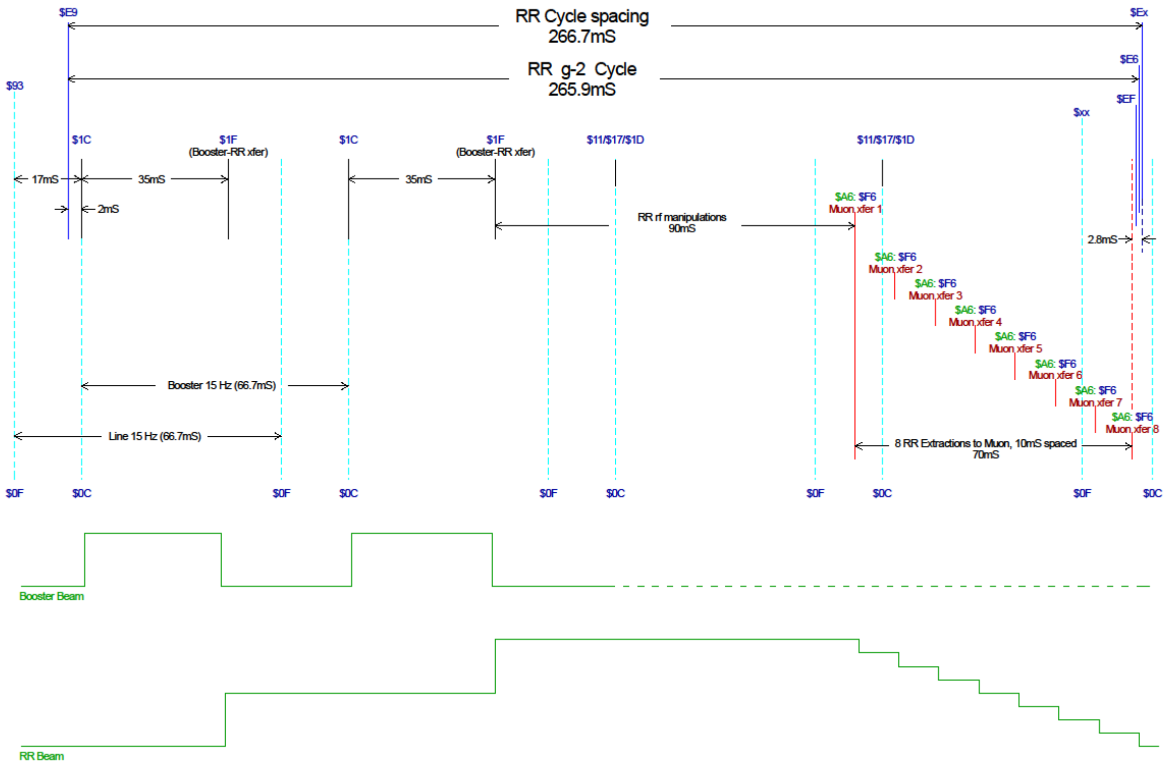

Figure 9: Detailed Time Line Generator module for the first half of a g-2 cycle.

4.4 Implementation

The accelerator complex does not need to be locked into only one of the scenarios described above. It is possible to construct time line modules for the TLG that implement each of the scenarios and alternate between them. For example, during g-2 running two 20 tick duration time lines could be constructed that do the following:

Time line A

- 12 Booster batches to NOvA (100% of baseline)
- 3 Booster batches to g-2 (75% of baseline)

Time line B

- 11 Booster batches to NOvA (92% of baseline)
- 4 Booster batches to g-2 (100% of baseline)

The fraction of operational time spent running with Time line A or Time line B would be a matter determined by Fermilab Program Planning. The details of these two time lines are shown in Figure 10.

To minimize the amount of accelerator retuning required when switching from one time line to the other, the construction of these time lines should be constrained by the following considerations:

- MI ramp waveform never changes
- Transfer from RR to MI always occurs at the same time in every module

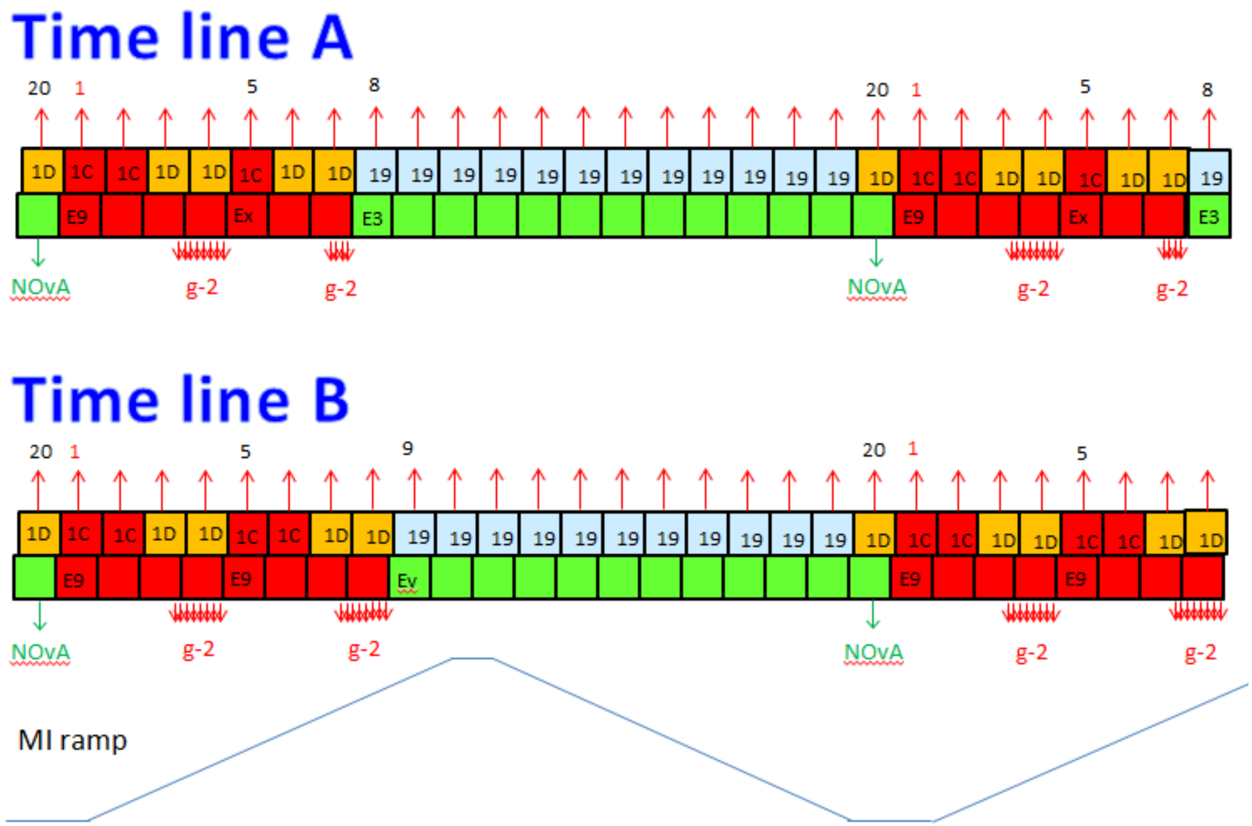

Figure 10: Two accelerator timelines for combined NOνA and g-2 running. Each time line is 20 ticks in length. Time line A favors NOνA running with 12 Booster batches designated for NOνA. Time line B favors g-2 with only 11 Booster batches designated for NOνA.

Similarly, two time lines could be constructed during combined NOνA and Mu2e running. Two 20 tick time lines that could be constructed in this case would do the following:

Time line A

- 12 Booster batches to NOνA (100% of baseline)
- 1 Booster batch to Mu2e (50% of baseline)

Time line B

- 10 Booster batches to NOνA (83% of baseline)
- 2 Booster batches to Mu2e (100% of baseline)

These time lines are shown in Figure 11.

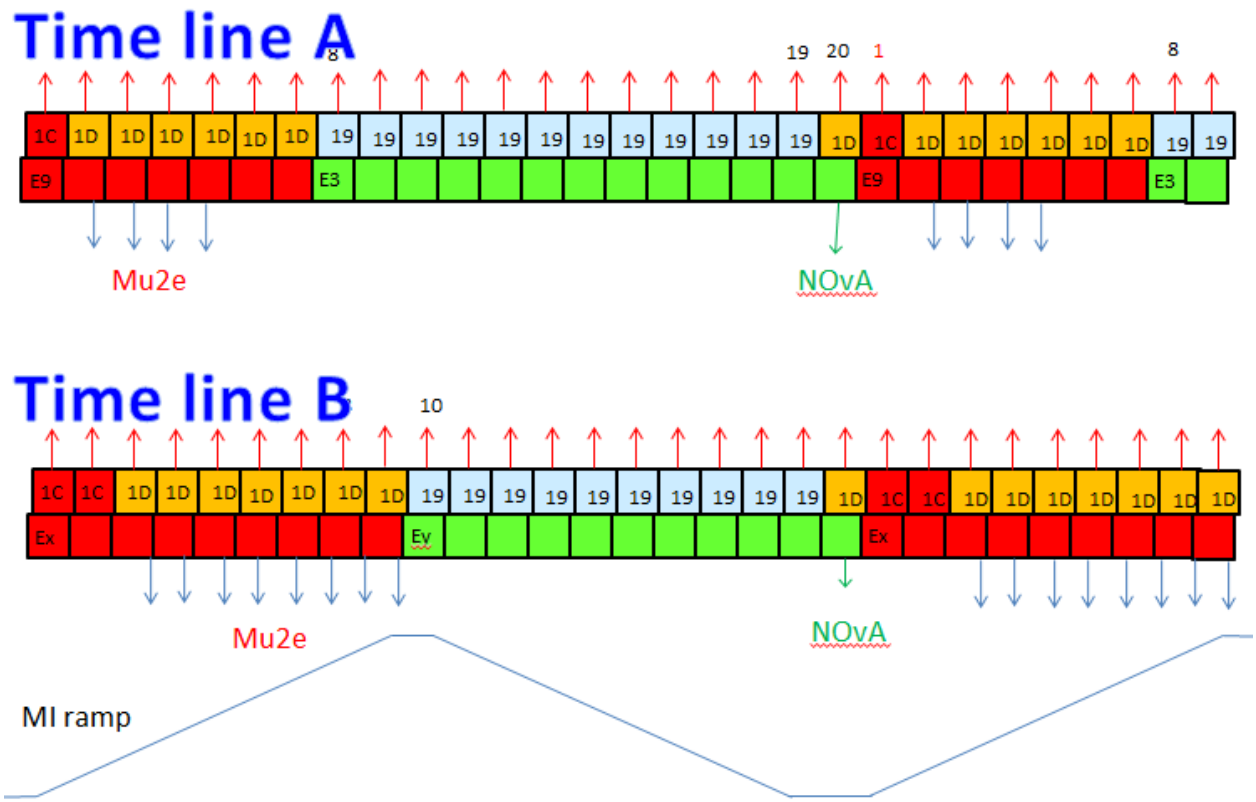

Figure 11: Two accelerator timelines for combined NOνA and Mu2e running. Each time line is 20 ticks in length. Time line A favors NOνA running with 12 Booster batches designated for NOνA. Time line B favors Mu2e with only 10 Booster batches designated for NOνA.

These alternate running scenarios could be used to fine tune the relative impact on NOνA and g-2 or Mu2e, or to take advantage of times when one of the experiments is either down, commissioning, or doing specialty runs.

5. Conclusions

The discovery of issues related to the beam delivery time lines for the g-2 and Mu2e experiments has prompted a detailed analysis of the beam delivery plans. Additionally, an assessment has been made of the impacts of various accelerator time line scenarios on these experiments..

The design beam formatting plans of Mu2e and g-2 are not compatible with a 1.33s Main Injector cycle with 12 Booster batches going to NOνA (under limitations of the present accelerator control system). Modifications to the baseline beam delivery plans to accommodate all of the accelerator timing constraints, as presently understood, results in substantial adverse impacts to the Muon Campus experiments. Alternatives, including increasing the cycle length to 1.4 s, spread the impact over all the experiments, including NOνA.

The time line can be quickly changed, at the discretion of Program Planning, based on experimental priority, as well as to allow one experiment to take advantage of times when the other is either down, or requires reduced beam intensity.

An full examination of possible modifications to the accelerator control system that could improve the situation does not fit within the scope of this taskforce. With greater effort and resources in that direction, further amelioration of the timing limitations could be explored.

References

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[3] P. Adamson, "*Timing for Muon Campus*" talk given to AD/Muon Department, Beam-doc-4714, November 20, 2014.

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